U.S. Department of Energy's

Office of Science

International Collaborations in the Fusion Energy Sciences Program

FY2010 Budget Planning Meeting

Gaithersburg, MD

March 11-12, 2008

Erol Oktay, Acting Director

ITER and International Division

Excellent Science Attractive Energy — Office of Fusion Energy Sciences

www.ofes.fusion.doe.gov

International Collaboration is a major contributor to the U.S. Fusion Program

- ITER - Provides a major facility for burning plasma experiments to the U.S. program
- Collaborations support ITER, complement the U.S. program elements and enhance scientific results
- International collaborations is an important factor in the emerging OFES strategic planning

International Collaboration is broad, integrated, and it draws on multiple resources in the program

A. ITER MIE – Well defined Project activities and budget

B. Most program elements support international collaborations indirectly:
   i. Major facility programs – ITPA experiments, databases, workshops
   ii. Stellarator, RFP, HEDP, and diagnostics related collaborations
   iii. Theory and Modeling activities and validation with experiments
   iv. Enabling Technologies – hardware development and physics support

C. Explicit budget line of 'International Collaborations (IC)' supports program-wide activities on foreign facilities

D. ITER Design Review – broad support from base programs and USIPO

All scientific exchanges in B and C categories and some of D are carried out through Bilateral, IEA, and IAEA agreements

Examples of Topical areas under Bilateral and IEA agreements

- **ITER scenario development:** JET, AUG, JT-60U
- **Disruption mitigation** studies on JET,
- **JET in-vessel visible diagnostic calibrations** using the JET robotic arm - prototype activity for ITER diagnostic calibrations
- **ELM control by stochastic edge** – TEXTOR and JET
- **NTM stabilization** – ASDEX-UG
- **Energetic particle studies** - JET
- **Particle control and plasma facing components** – JET, ASDEX-UG, Tore Supra and TEXTOR,
- **RF** - edge coupling and Electric Field measurements on long pulse discharges - JET and Tore Supra
- **High beta and long pulse integration** – JET and JT-60U
- **Steady state physics and technology**: EAST, KSTAR, SST-1
- **Superconducting tokamak operations –** KSTAR, EAST
- **Diagnostic development** – JET, TEXTOR, EAST,KSTAR
- **Negative Ion Beam development** – JT-60U
- **Dust Measurements and hydrogen retention** - Tore Supra

MAJOR U.S. FACILITIES, THEORY & MODELING, AND ENABLING TECHNOLOGIES ARE PARTNERS IN THESE COLLABORATIONS

Outline
and Background material

- Budget and Management summary of IC Budget line
- Role of international collaborations in the OFES strategic plan
  - New Opportunities
  - Priorities

- Background material for information
  - Technical Highlights from collaborations

Summary of Budgets and Management in the ‘International Collaborations’ budget line

International Collaboration Budget Line is Organized Primarily Around foreign facilities

($ in K)

	FY 2008	FY 2009
JET	$2,188	$2,130
KSTAR	1,649	1,625
Tore Supra	200	200
TJ-II	270	270
JT-60U	175	175
LHD	175	175
EAST	175	175
ASDEX-UG	75	75
TEXTOR	75	75
	$4,982	$4,900

U.S. Coordinators of Collaborations on Foreign Facilities

- JET :Jim Strachan
- KSTAR, SST-1 :Punit Gohil
- EAST :Vincent Chan
- Tore Supra/TEXTOR :Don Hillis
- ASDEX-UG :Earl Marmar
- JT-60U :Raffi Nazikian
- Stellarators : :Mike Zarnstorff

Institutional Participation in International Collaboration Budget Line

($ in K)

	FY 2008	FY 2009
PPPL	$2,472	$2,390
ORNL	1,194	1,194
GA	585	585
MIT	206	206
LLNL	20	20
Universities*	405	405
Nova	100	100

*Wisconsin, Columbia, UC Davis, Colorado School of Mines

Each Laboratory has a coordinator for multiple collaborative activities

- PPPL : Randy Wilson
  - JET, JT-60U, K-STAR, Stellarators
- ORNL : Don Hillis
  - JET, KSTAR, TS, TEXTOR, ASDEX-UG, Stellarators
- GA :Punit Gohil
  - KSTAR, EAST
- MIT :Earl Marmar
  - JET, KSTAR
- Individual PIs for grants
  - Sabbagh, McKee, Cecil, Luhmann, Levinton

Role of international collaborations in OFES strategic planning

Rationale for International Collaborations

- Goals and benefits
  - Enhance ITER support
  - Enhance scientific understanding
- All tokamaks emphasize ITER support
  - ITPA/IEA Joint experiments
- Some unique features of foreign facilities are:
  - Larger size, higher power, longer pulse, super-conducting coils, W walls, T operation, Ergodic Divertor….
- Complement US facilities
  - smaller size but flexible, extensive diagnostics, theory support, high field, low aspect ratio…

Some new facilities and hardware upgrades abroad

- JET – ITER Like Wall Project
- ASDEX – UG : All W Plasma Facing Component
- EAST, KSTAR, SST-1 – Superconducting tokamaks
- MAST upgrade
- LHD and Wendelstein 7-X
- EU-JA Broader Approach (JT-60SA, IFMIF, IFRC)

Greenwald Panel report provides international context

- Identified and prioritized broad scientific and technical issues to be answered prior to a DEMO
- Assessed available means to address these questions
  - Chapter 3 provides extensive details of U.S. and foreign facilities and programs
- Identified research gaps and how they might be addressed
- International collaborations should be an integral part of addressing some of these issues

Future Directions

- Opportunities for enhanced collaborations are available in a wide range of topical areas in support of
  - Burning Plasmas and ITER physics support
  - Steady state physics and technologies
  - Stellarators, STs, RFPs, HEDP, ICCs, Technology….
- Programmatic collaborations are providing proper priority for most of collaborations through their funding allocations;
- Need to enhance these collaborations with targeted funding of supporting diagnostics, hardware, and additional support through the IC budget line
- We need to prioritize collaborations among different facilities and programs based on
  - Programmatic interest in the U.S.
  - their time scales for providing beneficial data
  - Participation in EU-JA Broader Approach
- We have agreements in place to accommodate collaborations

Need community input

- Scientific collaboration with foreign fusion programs is essential
  - A part of ongoing programmatic activities
  - Exploit targeted opportunities
- Set the priorities for broad national interest collaborations within the IC budget line

BACKUP INFORMATION

- Technical Highlights from collaborations

ORNL International Collaboration Activities - FY2008-2010

Prepared by: **D.L. Hillis**

Prepared for :

DOE Budget Planning Meeting

March 2008

ORNL International Program

Scope and Strategy:

- ORNL international collaborations on JET, ASDEX-UG, KSTAR, TEXTOR, TJ-II, and Tore Supra make use of unique opportunities not available in USA domestic programs on DIII-D, C-Mod, or NSTX.

  Includes:

  - DT operation
  - size scaling,
  - long-pulse operation,
  - boundary configuration comparison
  - optimized performance (Impurity Seeding, divertor radiation,pellet fuelling, RF optimization, shear optimization…)
  - ELM control/mitigation

ORNL Collaboration Theme:

Particle Control and Performance Enhancements for Advanced Tokamak (AT) & Burning Plasma (BP) Discharges

ORNL International Collaborations are organized around a topical program

ORNL topical areas addressed at Tore Supra, JET, KSTAR, TEXTOR, and ASDEX-U are:

- Improved ICRF coupling via RF theory, modeling, and improved antenna design
- He Ash Diagnostics for high performance DT operation
- Particle Control with pellets and pumping
- Investigation of Hydrogen (H,D,T) pathways in Tokamaks
- Impurity Sources and transport (intrinsic and injected)
- ELM mitigation/control

T. Biewer(ORNL) on assignment to JET

Present Areas of ORNL Participation at JET
FY2008-2010

Collaborations with individual EU- Laboratories often means Joint Collaboration on JET

Physics elements

- **Hydrogenic (H/D/T) particle exchange**
  - **Wall changeover from D --> T; D --> H; D --> He**
  - **Trace tritium transport studies (tritium retention in wall materials);**
- **He transport & exhaust in ELMing H-mode and ITB plasmas**
  - **Modeling and experiments**
- **He Ash detection in high performance DT discharges**
  - **He Ash simulation experiments via He gas puffing and He beam injection**
  - **Core CXRS He Ash Diagnostic and CXRS Upgrade for JET-EP is now operational**
- **Recycling impurity(He, Ne, Ar) transport and exhaust**
  - **Impurity Seeding experiments and modeling**
  - **Develop scenarios for mitigation of heat fluxes due to ELMs using extrinsic radiators**
- **Importance of ELMs and ELM control in Transport Studies**
  - **ELM control in ITER relevant scenarios**
    - **EDGE CXRS Diagnostic for JET; first spectrometer being assembled**
    - **Diagnostics for ELM Pacing via pellet injection**
    - **Impurity characterization of new Be/W wall**
- **Participation in RF experiments using ITER like antenna**
  - **Attempt measurement of E-field in front of antenna via Stark Broadening**

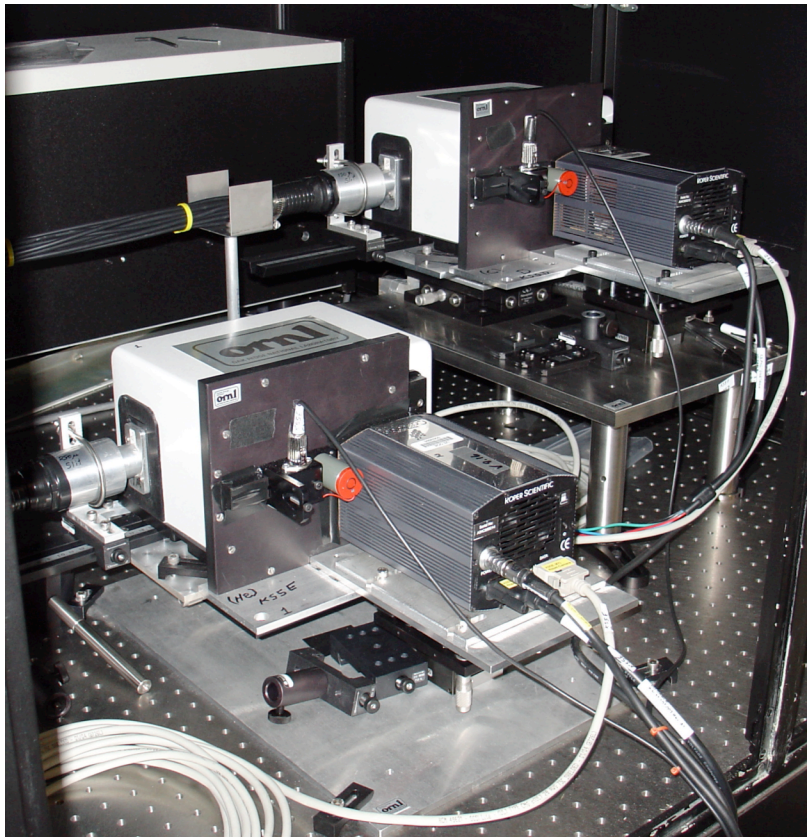
ORNL Hardware Related Elements for JET-EP & JET-EP2

- **He Ash detection in D-T plasmas**
  - ORNL Core CXRS Upgrade and Helium Ash Diagnostic ready for use during future DT operation of JET-EP (core measurement of He ash)
  - Upgrade detection efficiency of Penning System for detection of He ash in divertor during DT Plasmas. (divertor exhaust measurement of He ash)
  - In DT measurements Follow He ash from birth to burial

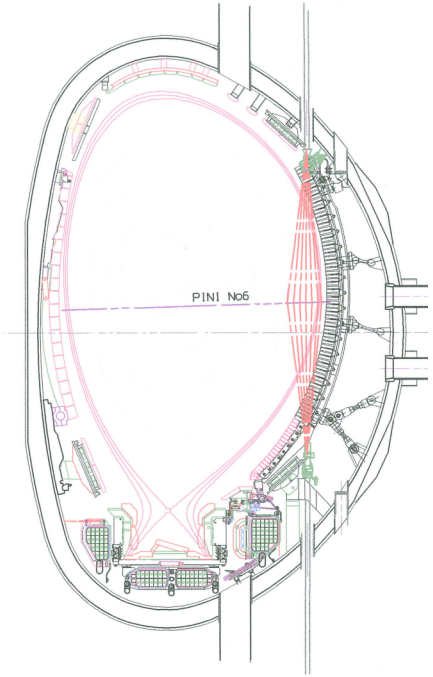
- **EDGE CXRS Diagnostic Upgrade**
  - Edge temperature, density, poloidal rotation, and Er profile measurements
  - Support ITER activity for "ELM Pacing during Pellet Injection"
  - Diagnostic provides real time data acquisition during a shot
  - Attempt measurement of E-field in front of antenna via Stark Broadening

EDGE CXRS Diagnostic upgrade for JET-EP2
(2008 - 2010)

Spectrometer Hardware for EDGE CXRS Upgrade for JET-EP2

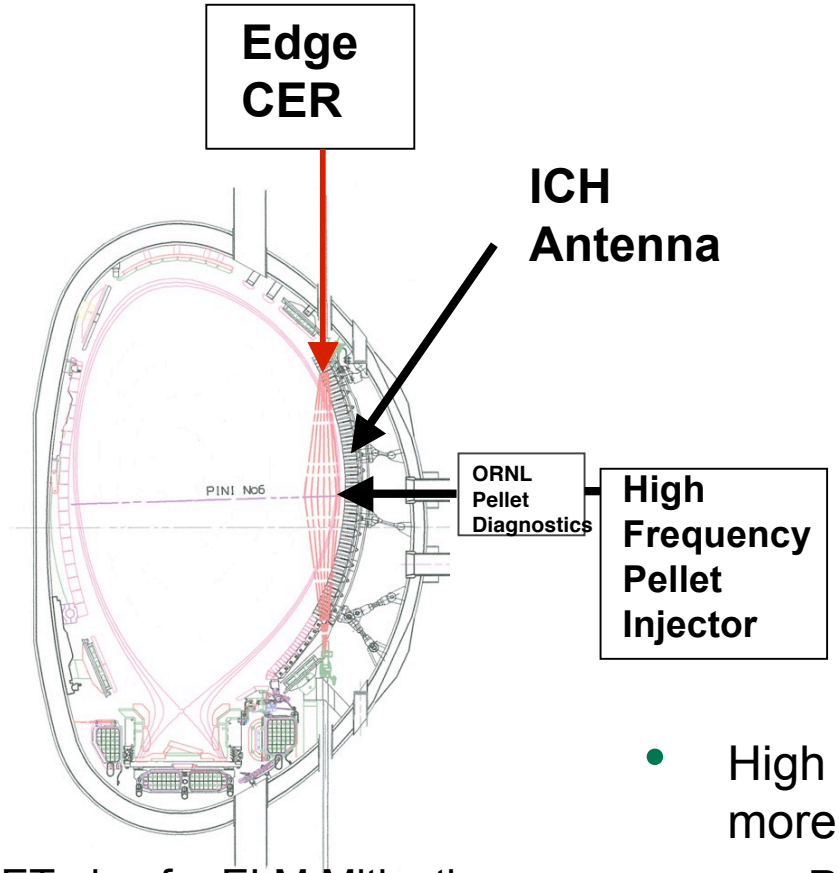


JET-EP2 EDGE CXRS Views

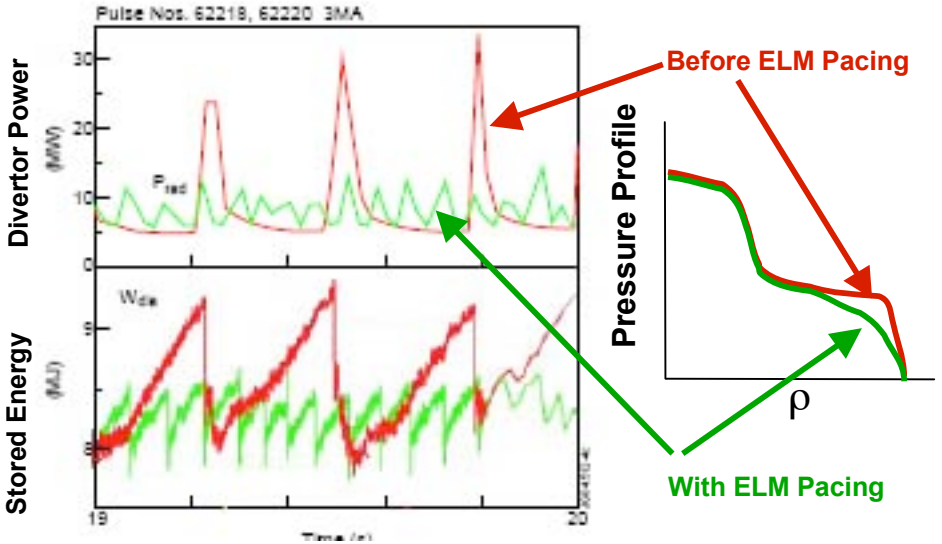


- ORNL has built and installed a Core He Ash Spectroscopy System for JET-DT
- Reproduce these spectrometers and CCD cameras for an EDGE CXRS upgrade for JET-EP2
- First spectrometer (Jan. 2008)

ELM Mitigation via Pellet Injection and Extrapolation for ITER



JET plan for ELM Mitigation with high frequency pellets and ORNL edge CER



4 Hz ELMs on JET are BIG,
20 Hz ELMs are tolerable

J. Pamela et al., 20th IAEA (2004) OV/1-2

- High freq ELMs from Pellet Pacing results in more favorable edge conditions
  - Reduced Heat flux to divertor
  - Increased ICH plasma loading stability
- Physics Interpretation from JET and DIII-D and ITER Extrapolation

USA/TEXTOR-DED COLLABORATION
Activities FY2008-FY2010

D. Hillis, J. Hogan, and L. Owen (ORNL)
R. Moyer (UCLA) and T. Evans (DIII-D)
N. Luhmann and C. Domier (U.C. - Davis)
H. Park and E. Mazzucato (PPPL)
T. Munsat (U. Colorado)
T. Donne (FOM)
P. Woskov (MIT)

prepared by: D.L. Hillis

March 2008

for DOE Budget Planning Meeting

ORNL/TEXTOR Collaboration

Activities 2008-2010

ORNL activities with TEXTOR Team are focused on joint participation in JET Experiments via Trilateral-Euregio cluster

- Impurity Seeding Experiments at JET
  - Particle Exhaust including He, Ar/Ne recycling, & ELM control in H-mode discharges
- H/D/T wall changeover experiments at JET (V. Phillips)
- Impurity concentration measurements in the sub-divertor of JET utilizing the ORNL-TEXTOR Penning gauge
- Preparation and planning for JET ITER wall change over
- ITPA benchmarking activities with SOLPS5/Eirene with UEDGE (L. Owen, D. Coster, & D. Reiter)

Joint Experiments (DIII-D, NSTX, & TEXTOR) and EMC3-Eirene Modelling of RMP & DED Experiments

- Ergodic Edge modeling using EMC3 - Eirene and SOLPS
- New ORNL Post-doc (E. Unterberg) at DIII-D working on RMP and modelling with Moyer, Evans, and O. Schmitz(TEXTOR)
  - Heat flux measurements observed on RMP (TEXTOR group)
  - Particle flux and recycling measurements observed with RMP (ORNL group)

DIII-D/TEXTOR Collaboration on Stochastic Effects in Tokamaks

T. Evans (GA) and R. Moyer (UCSD)

- GA &UCSD scientists are involved in several collaborative research efforts with scientists from TEXTOR and the FZJ, including:
  - study of stochastic layer transport and it's role in ELM suppression by edge resonant magnetic perturbations;
  - evaluation of the performance of ITER-relevant diagnostic mirror in the DIII-D divertor;
- Study of carbon dust dynamics in TEXTOR and DIII-D
- Continued experiments are planned on stochastic edge experiments both at TEXTOR and DIII-D
- TEXTOR, UCSD, GA, and ORNL are jointly studying the stochastic edge through modelling using the 3D Edge code (EMC3-Eirene) where ELMs are suppressed via the Resonant Magnetic Perturbation (RMP) coils or DED.

Microwave Imaging Reflectometry (MIR) and Electron Cyclotron Emission Imaging (ECEI)

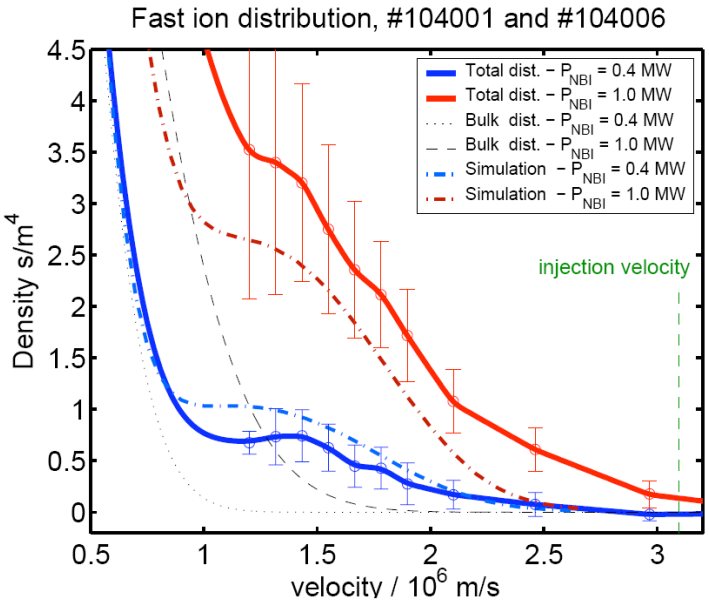
N. Luhmann and C. Domier: U.C. - Davis
H. Park and E. Mazzucato: PPPL
and T. Munsat: Univ. of Colorado

- **ECEI measures density and temperature fluctuations**
  - 2D imaging system is now in routine operation
  - 128 channels for Te fluctuations
  - Provides real time images of sawtooth oscillations and magnetic reconnection processes
  - US (UCD) team successfully implemented the new improved ECEI modification
- **MIR system is still in commissioning phase**
  - Series of MIR system tests showed a discrepancy in the reflected signal between the artificial conductive layer with the proper curvature and that of the plasma.
  - The correlation length of the amplitude signal is significantly broader than that of the phase signal and more sophisticated experimental tests will be conducted to clarify the fundamentals of the reflectometry based on TEXTOR data.
  - Work is still underway to provide density fluctuation measurements
  - Further improvements expected in 2008

Fast Ion Collective Thomson Scattering

P. Woskov, Intern. Collaboration with Risø, Denmark

- **TEXTOR 110 GHz CTS diagnostic operational**
  - Fast Ion plasma measurements being obtained in NBI and ICRH plasmas
  - 1-D fast ion velocity distributions have been experimentally inferred inside the core of a tokamak and compared to theory



- **TEXTOR Gyrotron frequency studies have been carried out**
  - Frequency chirp during pulse, plasma feedback perturbation

- **Risø will continue to study and refine TEXTOR CTS diagnostic**
  - Explore operating limits of CTS
  - Improve operating robustness and reliability
  - Continue CTS physics studies of fast ions
    - ICRH physics for insights on fusion alpha absorption
    - Fast-ion/plasma wave interactions and sawteeth redistribution

Tungston Lamella tile Development

E. Marmar and B. Lipschultz

- Discussions in May and November 2007 at Culham with the JET & Juelich engineers on Tungston Lamella tiles
- The MIT lamella tiles (one complete toroidal ring in the high heat flux region of the outer divertor) have now been installed and used for more than one campaign.
  - They have so far operated well. Tiles have been removed for further analysis.
- MIT will stay in contact with both the Juelich and JET groups to discuss C-Mod operational experience, the construction progress of the JET tiles, and finally, the operational use on JET.

USA/Tore Supra COLLABORATION
Activities FY2008-FY2010

D. Hillis, W. Gardner, and L. Owen (ORNL)

prepared by: D.L. Hillis

March 2008

for DOE Budget Planning Meeting

ORNL - Tore Supra Collaboration

Unique Features of Tore Supra

- long pulse (~ 360s) with high power density (< 5 MWm^{-2}) on carbon with H_20 cooled Cu
- will increase steady state LH power to 8 MW, and ECRH to 3 MW.
- "short pulse" ICRH capability (9 MW for 40s) will be maintained.

ORNL Research Focus areas in FY2008 - 2010 on TS

- **RF heating**
  - –New ITER-like ICRF antenna
  - –RF-edge interactions
  - –Bulk ion heating with ICRF
  - –Attempt measurement of Electric Field in front of RF antenna via Stark Broadening
- **Carbon**
  - –Tritium retention in Carbon: gas balance, post-mortem analysis, and modelling
  - –Carbon erosion and migration
- **Dust characterization in long pulse discharges**
  - •collaboration with C. Skinner(PPPL)
  - •Evaluation of Hydrogen retention of dust particles

ORNL/ASDEX-U COLLABORATION
Activity Report for 2008-2010

D. Hillis, R. Maingi, and L. Owen

ORNL

March 2008

for

DOE Budget Planning Meeting

ORNL/ASDEX-U Collaboration

Activities 2008-2010

ORNL work with the ASDEX-U team focuses on divertor modeling

Application and development of the Jülich-Garching SOLPS5 code (also known as b2-EIRENE) to DIII-D, JET, and ITER, especially for ELM behavior

Focus of work is to develop an extrapolable model for ELM effects on particle transport (e.g., helium in ITER). As part of this, to assess the relative strengths and weaknesses of the existing divertor modeling codes SOLPS UEDGE and EDGE2D.

Current Activity: (FY2008)

- participating with IPP-Garching and ITER in the ITPA benchmark of the EDGE2D, SOLPS, and UEDGE divertor codes
- D. Coster (IPP-Garching) to visit ORNL March FY08 to continue benchmarking activity.
- the impurity generation model in SOLPS has been improved to include effects of micron-scale dust particles on the divertor target.
- convective ELM model derived from comparison with fast mid-plane CER in DIII-D has been applied to analyze JET ELM mitigation experiments

Future Work: (FY2009-FY2010)

The SOLPS code suite will be used in modeling DIII-D, JET, and ITER to develop an integrated model for ELM behavior, both for impurity enrichment (including helium) and to develop successful ELM heat flux mitigation scenarios.

ORNL/KSTAR COLLABORATION
Activity Report for 2008-2010

D. Hillis, L. Baylor, R. Colchin

ORNL

March 2008

for

DOE Budget Planning Meeting

ORNL/KSTAR Collaboration

Activities 2008-2010

ORNL work with KSTAR Team on diagnostics

Focus of work is to :

- install ORNL filterscope system and support first plasma operation on KSTAR in June 2008
- provide assistance in implementing a CER diagnostic on KSTAR
- work with KSTAR staff to arrive at specifications for pellet injection system

Current Activity: (FY2008 - FY2010)

- finalize filterscope installation for monitoring H-alpha, ELMS, and impurity radiation during first plasma operation
- work with KSTAR staff to arrive at specifications for a pellet injection system and begin conceptual design of pellet guide tube for inside launch
- provide support to KSTAR staff for visible diagnostics during first plasma operation

International Collaboration Highlights BPM 2008

PPPL Contributions

March 12, 2008

US-KSTAR Workshop and Completion Ceremony

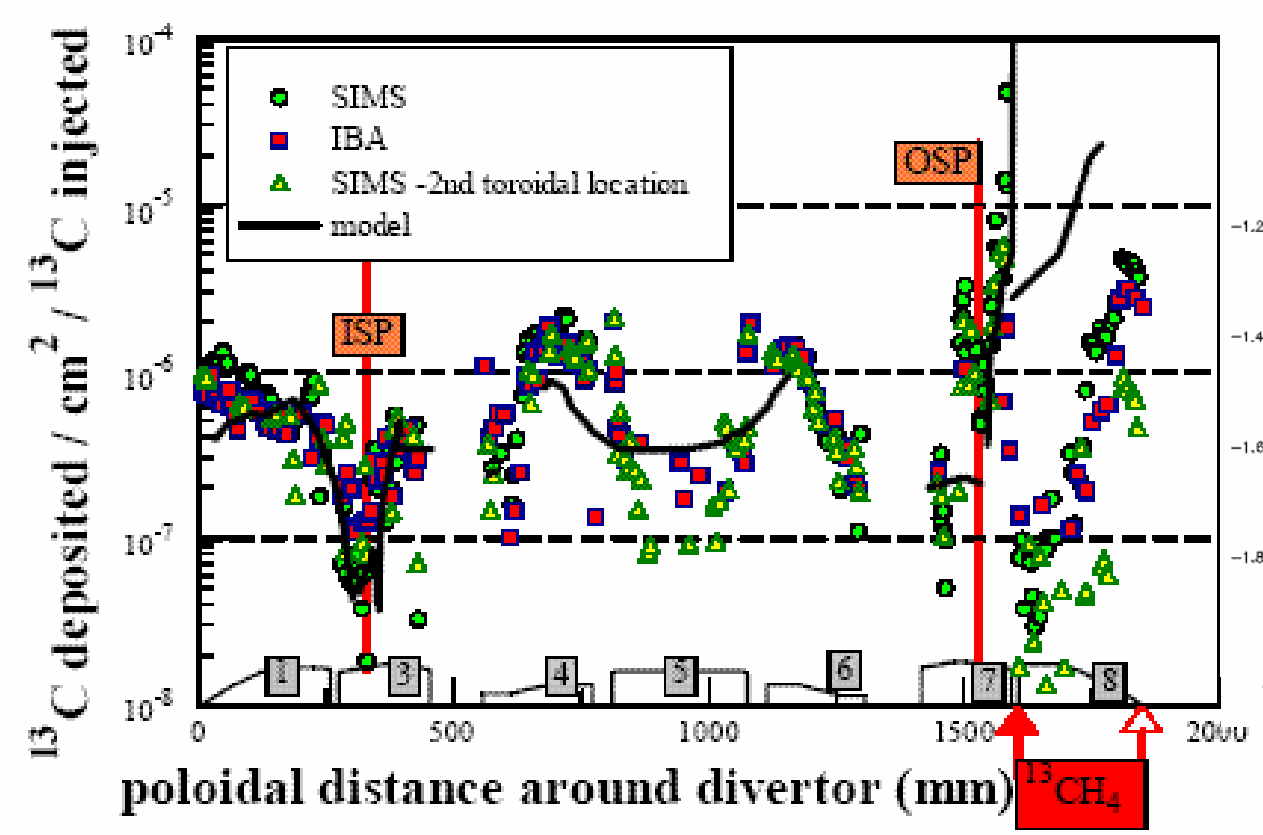
- Workshop concentrated on plans for KSTAR operation in 2008

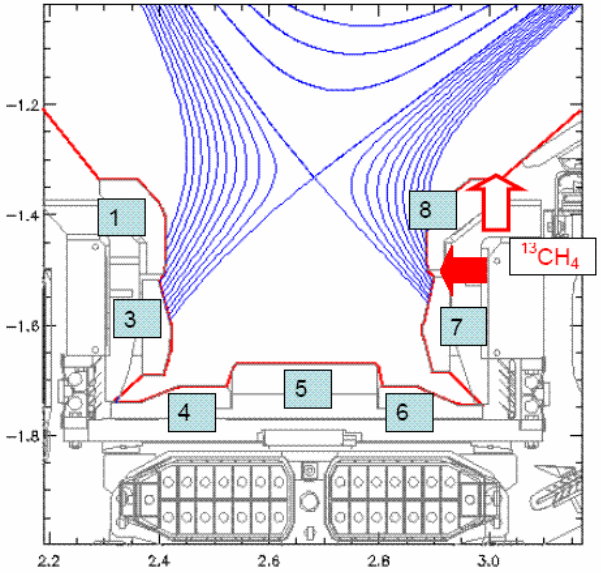
Fig.1. (a) Ceremony for the construction milestone of the KSTAR is shown. The President of Korea (third from the right side) Director of ITER (second from the right side) (b) The US participants are shown with the completed KSTAR device.

PPPL Constructed and delivered to KSTAR a Shutter Mechanism for Thompson Scattering

EDGE2D modelling of the ^{13}C deposition from the JET experiment indicates several migration pathways including:

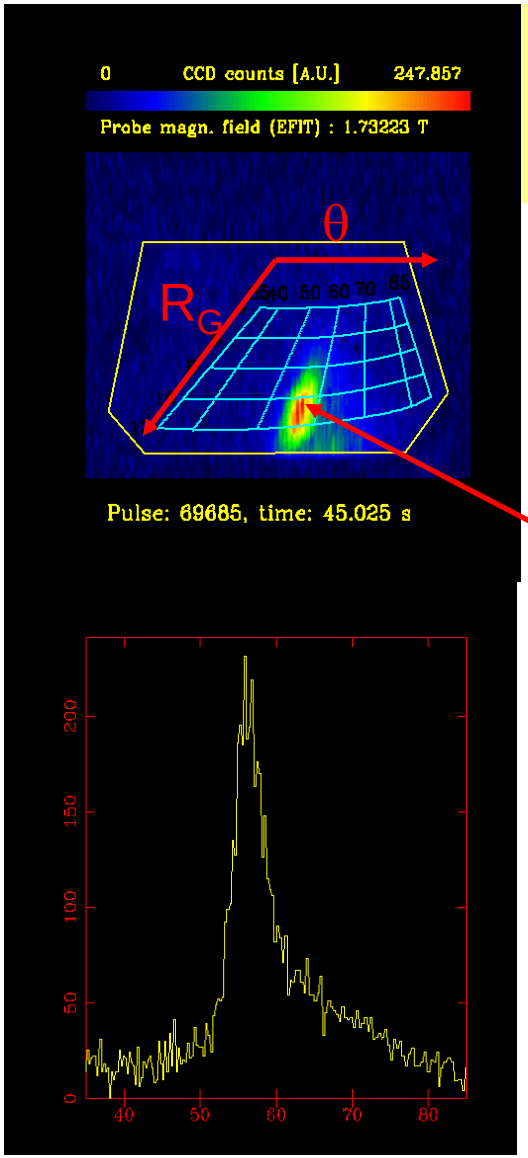
1. Leakage out of divertor and travel through the main chamber SOL
2. Ion migration through the PFR
3. Erosion/recycling movement along the outer target
4. Neutral carbon transport through the PFR





J. Strachan

TF Ripple loss in JET AT plasma



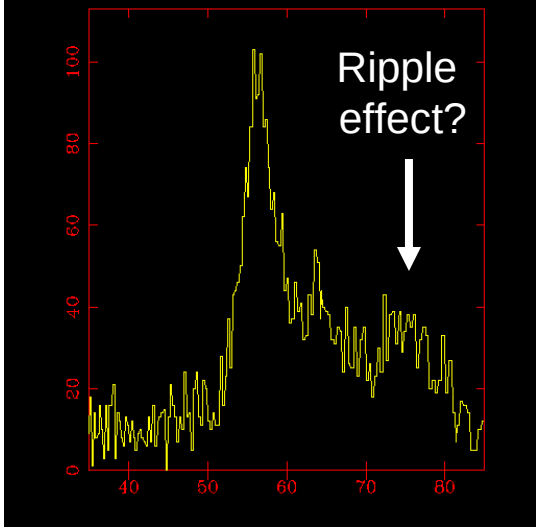
Scintillator Probe results

NBI off-axis

P_{NBI}= 8.5 MW & 9 MW

P_{ICRF}= 3.7 & 3.8 MW

Tail protons
$<E_p>$ ~ 1.6 MeV
and deuterons
$<E_d>$ ~ 0.8 MeV



No ripple

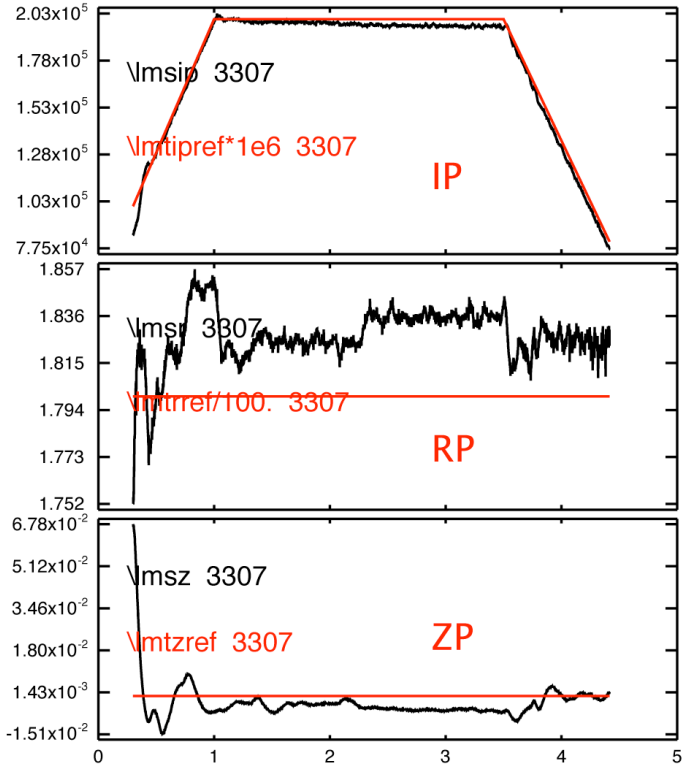
Ripple: I_{min} / I_{max} = 0.5

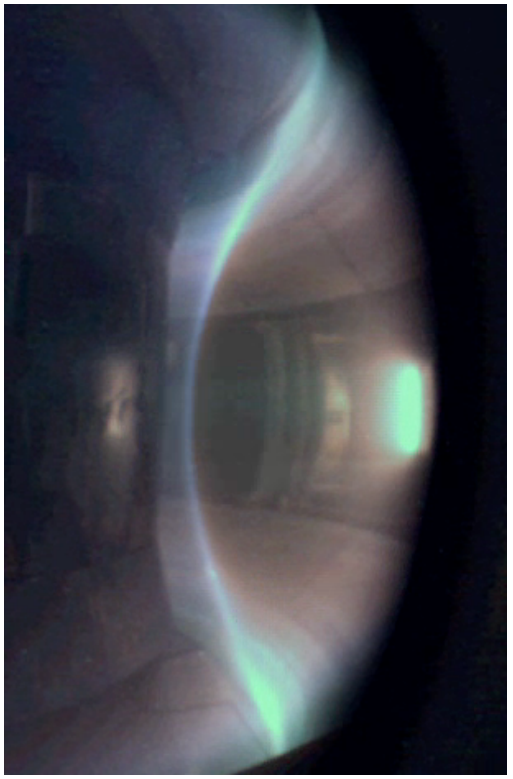
V. Kiptily, et al., IAEA TCM Energetic Particles, October 2007

DIIID-Supplied PCS an Integral Part of Successful EAST Startup and Initial Plasma Campaigns

GA-built hardware and PCS software delivered/installed at ASIPP (EAST)

On-site support by DIII-D/PPPL scientists and programmers for 1st plasma operation (circular plasma; Ip,R,Z control)





DIII-D/PPPL on-site support for 1st diverted plasma operation

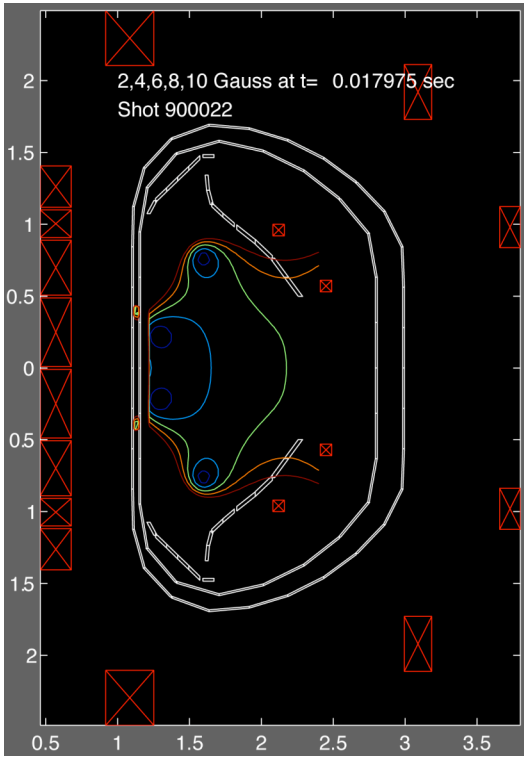
DIII-D NATIONAL FUSION FACILITY

EAST

GENERAL ATOMICS

DIIID-Supplied PCS to be Used in KSTAR Startup and Initial Plasma Campaigns

- KSTAR PCS on schedule to support first plasma
- Suite of software tools delivered with PCS accelerates control development and testing
- PCS successfully controlled single PF power supply in December pre-commissioning
- GA currently supporting preparations for first plasma operation
- On-site support by DIII-D/PPPL planned for device commissioning and first plasma operations in May-June 2008
- KPCS v.3.0 (includes rtefit and isoflux control) will be ready for first diverted plasmas
- On-site support planned through first diverted plasma operations in early 2010



"Hardware-in-the-loop" Simulations Enable Realistic Evaluation of KSTAR PCS Control and Power Systems' Capability for Breakdown

DIII-D NATIONAL FUSION FACILITY

KSTAR